EFFECTS OF SLOPE AND APEX ZONE GEOMETRY OF GLULAM BEAMS WITH SPECIAL SHAPE ON THEIR DESIGN

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ABSTRACT:

This paper represents a part of diploma work in the scope of glued laminated beams of special geometry. The main subjects of research we have made are glulam pitched cambered beams and curved beams. An unsuitable form, e.g. inappropriate slope and shape of apex zone, due to the span and radius of curvature of the curved zone, could provoke very serious problems in practice and jeopardize a safety of the whole structure. Wood is anisotropic material whose tensile strength perpendicular on fibres is far below the rest of its material properties and we must deal very seriously with the safety of the curvature zone of girder, where these stresses appear with their maximum values. Codes make some simplifications in limit states design of these girders. These simplifications are acceptable enough in engineering practice, but we tried to compare results obtained by rules included in EN 1995-1-1 and DIN 1052, linear static FE analysis and theoretical models. We also presented some practical advises for their design and practical application..

1. INTRODUCTION

From the aspect of architecture, pitched cambered glulam beams of great intrados curvature are aesthetically very attractive and desirable shapes of main girders. On the other hand, from the structural and technological viewpoint, the complex geometry of those girders is a potential limit to their economic application. A big intrados curvature in the apex zone, non linear distribution of stresses along the cross-section depth and both a complex state of stresses caused by girders geometry and wood anisotropy make it necessary to handle the calculation of those girders carefully. As for their mechanical resistance and stability, the study of tensile strength perpendicular to grains is of enormous significance and is intensified by curvature. The load-carrying capacity of wood in regard to tension perpendicular to grains is exceptionally low and varies significantly from its other mechanical properties. It is therefore hard to optimize the dimensions of these girders according to this criterion since its other characteristic cross-sections are not used enough. Such a problem can be avoided in different ways: local strengthening of the curved area, the construction of ridge girders of reduced static height (rounded ridge) or the construction of girders in couples instead of uneconomic increase of the single girder's height. Much better solutions relate to the geometry's rationalization (the slope of the flat girder's part of the axis, the raise of the curved area radius and the variation of the static height – full or reduced, modifying or constant girder's height as well) in relation to the span. The paper advocates such an approach, and the results lead to the summary of guidelines for a practical usage. New European standard, EN 1995-1-1:2004 were taken as the basis for an investigation. We compared the results with those of the calculation according to pre-norms, DIN ENV 1995:2000-1-1. The verifications for mechanical strength and stability of the characteristic section x-x relevant for the stability control differ in the EN and DIN ENV codes. The FE 2D and 3D girders' models are parametrically prepared as well, undergoing the static analysis and global stability analysis (buckling) in order to look at the impact of simplification which leads to the practical implementation of standards for design of timber structures. Set of coefficients applied in expressions and rules given in standards transform the non-linear stress distribution with respect to the depth of the cross- section into a linear one, and a complex stress state transforms into bending stresses. FE analysis done in COSMOS/M package reflects a real state of stresses and deformations. Therefore, we wanted to investigate whether, and to which extent are the practical proofs of mechanical strength and stability on the side of safety.

2. PARAMETRIC ANALYSIS

2.1. Assumptions and methodology

The constants in the calculation are as follows:

1. Mechanical properties (strength, stiffness modulus, density) of comparable classes of glued laminated wood with high load-carrying capacity assigned to service class 1 – BS 28H (DIN ENV 1052:2000) made of structural timber S13 strength class / GL 28H (EN 1995:2004) made of structural timber C30. Special 1st strength classes BS 16H / GL 32 H have been considered also.
2. The 5,0m distance of main girders and characteristic short-term load of 1,25kN/m^2 while the characteristic permanent action including dead load has been estimated to be 0,7kN/m^2.
3. Symmetric geometry and symmetric load of main girders (the asymmetric wind impact omitted).

The application of programme packages and the approach to the calculation (parametrically conducted analyses):

1. Programme package MATCHAD has been used for the verifications of limit states where the main girders are modelled parametrically (seven input parameters described shape and geometry: intrados and extrados slope angles, α and β, their divergence, γ, girder span, L, chord length on the intrados dependent on the radius and central curvature angle, C_{in} (the affecting volume of the curved apex zone, V_{ap}) and cross-section dimensions: the depth on supports, h_a and the width, b). The alteration of stresses and the verification of the cross-section's load-carrying capacity (satisfying or not) result from varying the input parameters. Possibility of reinforcing of highly curved apex zone has been also considered, as a practical alternative to over-dimensioning.
2. The Excel programme has been used for limiting the input parameters values (α, β, γ, L, C_{in}, h_a, b) so as to evaluate the girder's rationality (dependence of mechanical strength and girder's stability on geometry). With regard to limitations of the study scope (samples' number, simplified analysis only for symmetrical conditions, etc.), rationality assessment for the glulam beams with highly curved apex zone can be considered as a design «guideline». Effect of curvature (h_{ap}/R) and geometry of apex zone has been included in parametric design by varying the chord length of the inner edge of curved zone, respectively to the girder's span, L (C_{in} = L/4, L/3, L/2).
3. The COSMOS/M programme package has been used for FE analysis of parametrically modelled girders (the same input parameters) undergoing the same analysis and repetitive calculations. As the last step of research, that provided possibility of comparing results with those obtained by procedures in accordance with design codes (EN 1995, DIN ENV 1052).

2.2. Analysis obtained on various types of glulam main girders of special geometry

The calculation's procedure diagram (see Fig. 1) shows the ways in which the girder's calculation and the analysis of design's rationality along with the construction of related girders were conducted. The paper presents the required stages to dimension accurately and rationally the girder (pitched camber and/or curved girder of high intrados curvature, see Fig. 2). The girders are simple supported on its span, and the curvature range is of $2 \leq R / h_{ap} < 10$. The design of these girders is technologically far more complex as the axis in the apex zone is designed by inserting the small radius curve. The number of phases and the mode of gluing the laminations affect the static height and the load-carrying capacity in the apex zone (full or reduced cross-section of pitched cambered girders). The cross-section depth in the apex should be restricted to 2,5m due to production (prevention of delaminating) and transportation hindrances. The curved area's volume V_{ap} limitation is 2/3 from the total girder volume V_b. while the transversal slope of these girders should not exceed 25°. There is also an additional limitation related to the value difference $\alpha - \beta \leq 10°$ for the pitched cambered girders with tapered non-curved zones. Such a condition results from the fact that the laminations run parallel to the inner edge of beam (curved edge). Therefore, the effect of oblique slashed edge appears on the opposite edge (outer edge). The unsuitable effect that tapered geometry has on the values of components of complex stress state gets modified by limiting the edges' slope difference. In the practice, the shapes of pitched cambered girders of curved intrados can be constructed so that their static cross-section depth in the apex zone gets reduced (fitted apex), whereas the constant remains (concentric curvature). Due to the reduction of static depth in the apex zone they are treated as curved girders. In the zone where the girder's axes are straight, depth of girder's cross-section can be either changeable or constant.

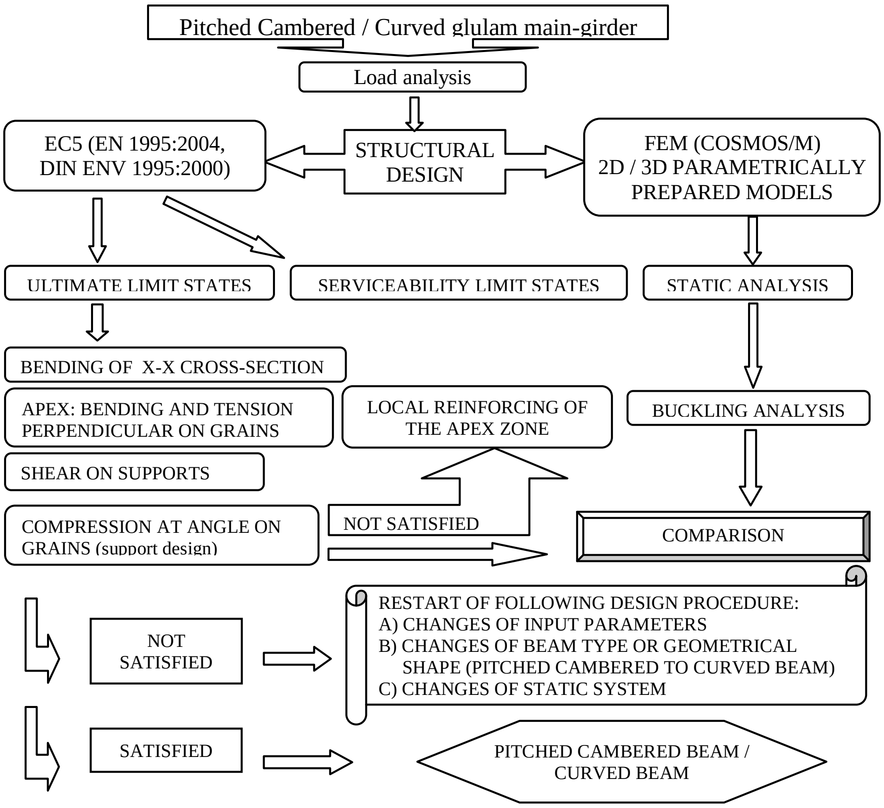

Figure 1: Flow-chart of parametric analysis obtained on various types of beams of special geometry

The comparison of the design according to ENV and EN does not show major differences in the utilisation and safety. As far as the calculations are concerned, the only difference relates to the treatment of the characteristic cross-section x–x on the girder's flat part, where the difference in the cross-section utilisation (bending and stability), in the notched extrados is 30% – 36%, and the calculation according to EN 1995-1-1:2004 is on the safety side related to DIN ENV 1995-1-1:2000. The difference in the utilization of cross-section x– x on the lower flat intrados is little and amounts some 15%. The comparison with FEA shows that the impact of longitudinal force (visible in FE models) for the girders with a usual bearing combination (unmovable and movable) is negligible. Therefore, the simplifications applied in the standards are practice related and acceptable from the engineering point of view, in laboratory research and the theory of anisotropic plates. The cross-section with the highest bending stress (x-x), comparison of FEA and EC5 shows that standards are on the safety side (see Fig. 2).

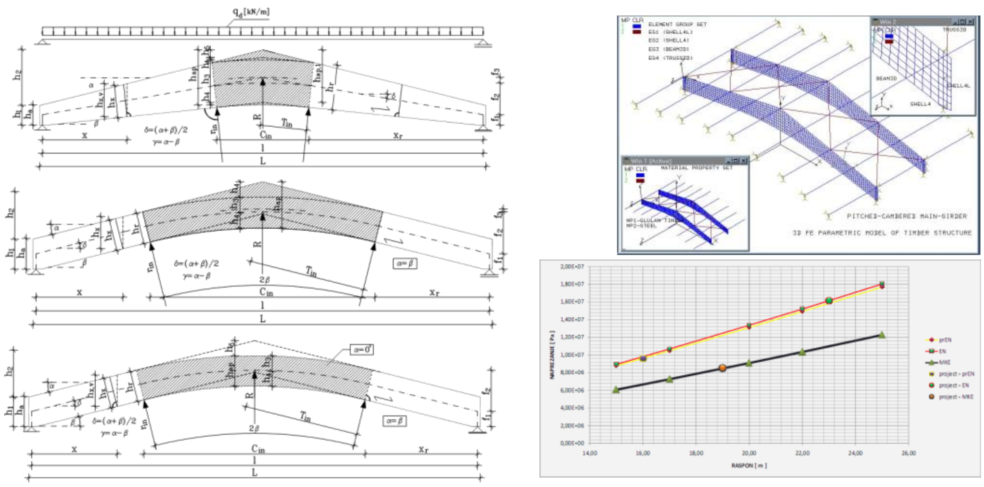

Figure 2: Types of glulam beams (left), FE 3D model for type 1 (right) and comparison of results of parametric design procedure for type 1 (EN 1995, DIN ENV 1052, FEA in COSMOS/M)

The analysis conducted for the typical girder geometries show that aesthetical arguments prevail over economical ones. The anisotropic properties of timber, the geometrical shape and low perpendicular tension load-carrying capacity of the curved zone (the prevailing criterion for design) make the application of this type of girders (simply laid on the two supports) non-rational, especially because of the low exploitment of the girder in the straight zone.

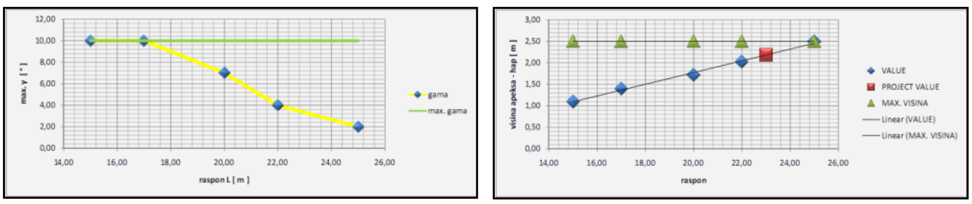

Figure 3: Type 1(BS 16H) – input parameters, limitations (γ, h_{ap}) and results of parametric design

The performed analysis shows that the increase of the curved zone radius has a beneficial influence on shaping and stress distribution along longitudinal axis, therefore, the value of intrados chord C_{in}

should not exceed 0,5L if we want to fulfil $V_{ap} \leq 2V_b /3$ criterion. An additional condition, important to avoid occurrence of unpleasant stresses in curved laminations, should be the limitation of $r_{in}/t \geq 240$ ratio (where r_{in} is radius of inner curved edge, and t is lamination thickness). Such an approach in the girder design has a beneficial influence on the rationality of the structure. An alternative approach to changing the shape or type of the girder in order to increase the load-carrying capacity of the curved region is to strengthen the girder with reinforcing bars in the curved zone. This implies a reduction in the girder height because of the great increase in the perpendicular tension load-carrying capacity (Fig. 5 and 6). In that case, the main design criterion become the bending resistance of cross-section in apex (for curved beams, type 3) or bending resistance of characteristic cross-section on the straight part of the girder (for pitched cambered beams, type 1). Combined bending and axial compression should not be neglected wherever it occurs. For reinforcement (see Fig. 4 and 5), glued-in threaded bars, self-taped screws, LVL or glued plywood plates can be used (the compression of the adhesive can be additionally enforced by nails or dowels).

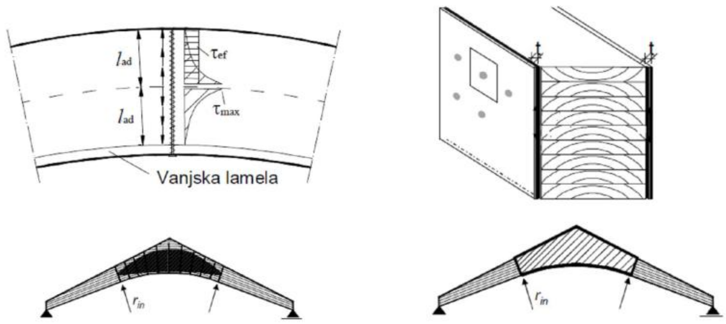

Figure 4: Strengthening of curved zone – practical solution to prevent over-dimensioning: self-taped screws or glued-in threaded bars (left), LVL or glued plywood plates (right)

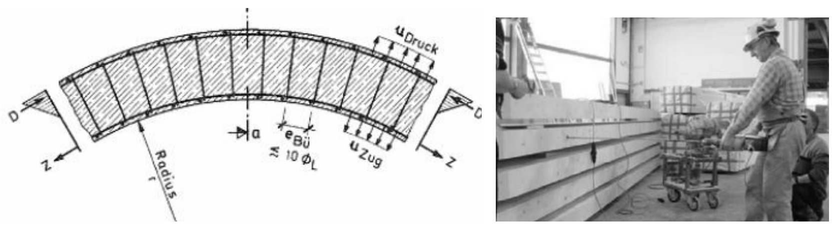

Figure 5: Glued-in threaded bars or self-taped screws: arrangement and embedding

Although the EN 1995 design code does not provide the rules for calculation of the reinforcement of the curved zone, it will be based on the assumption that the tensile stresses perpendicular to grain are accepted by the reinforcing bars (the contribution of timber is completely ignored). The approach used in this analysis is based on the DIN ENV 1052 design code which presumes the partial involvement of timber in load bearing of the tensile stresses perpendicular to grain (the reinforcing bars replace the lack of bearing capacity). According to this, in the parametric analysis the next approach has been used: the exceeding in resistance of the curved zone in tension perpendicular to grain is limited to 250 %, and the exploitment of the bending resistance is limited to 50 %. Results of this type of analysis are based on the formerly introduced input parameters (see Fig. 6).

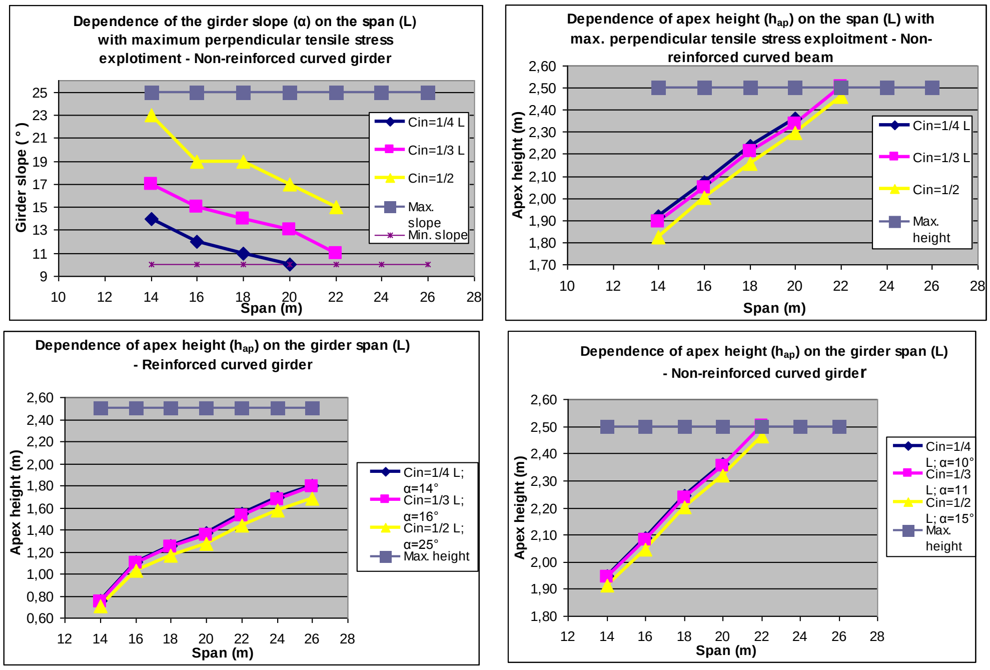

Figure 6: Type 3 (BS 14H) – input parameters, limitations (α, h_{ap}) and results of parametric design

3. CONCLUSION

Although it is easy to select parameters with significant influence on load-carrying capacity of beams with curvature inner edge, more difficult task is to carry out true recommendations for their better design fulfilling the criterion of rational exploitment of material at the same time. Analysis of effect of slope and geometry shape of their apex zone on their design might be useful in preliminary design level and evaluation of structural acceptability. Since the tensile stress perpendicular to grain prevails in the design of this type of beams, we have demonstrated that with the increase of the span, which should not exceed 25 meters, the increase in the radius of curvature decreases significantly the negative influence of this type of stresses. The pitch cambered girders with tapered straight zones have shown the best results from the viewpoint of balancing the bearing capacity and the exploitment of the material. The increase in the span must be accompanied by the increase in the angle of the beam and the reinforcing of the curved zone is a rational solution for larger spans and angles. Comparison of FE analysis and those obtained in accordance to standards for timber structural design we get to the difference in the distribution and values of results which is confirmed by the connection with the slope. Both design methods include conforming to the stress increase trend, but not with the stress magnitude.

4. REFERENCES

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